

Final degree Thesis

Grau en Enginyeria en Tecnologies Industrials (GETI)

Demand analysis and Low Voltage DC sizing of a renewable energy based microgrid in Bangladesh without AC connection

REPORT

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Abstract

Millions of homes doesn't have access to grid connection in Bangladesh. Off-grid renewable based systems are breaking through in rural areas. These microgrids usually rely on solar energy and also batteries are implemented.

This report deals with the modelling and operation of a network interconnecting several households that include solar systems. Each solar system includes ones solar panel, one battery and one unit of load. This approach is compared to a more centralized version, in terms of power losses, where the production and consumption are connected separately.

Nevertheless, the energy supplied is not enough as electrical needs go increase. That's why this report studies the demand evolution in detail in order to improve the quality of life of grid users. It is revealed that a new sizing is required for existing Low Voltage DC microgrids consisting on adding more solar panels and batteries until demand is fulfilled. This sizing is obtained with the help of adapted MATLAB programs created by Masters Students from UPC real data.

Contents

1	Preface	6
1.1	Renewable energies in the world	6
1.2	Electrification process in Bangladesh	6
2	Introduction	8
2.1	Objectives	8
2.2	Scope of the project	8
3	Previous work done	9
3.1	Design of a low voltage DC microgrid using Matlab	9
3.2	Context and objectives	9
3.3	Modelling	9
3.4	Topologies	10
4	Case study	14
4.1	New modelling	14
4.2	Converter-less topology	17
4.3	Converter connected to PV topology	18
4.4	Converter connected to batteries topology	19
4.5	Converter connected to batteries and PV topology	20
4.6	Shadow study	21
5	Time-domain simulation	24
5.1	Starting point	24
5.2	Demand profile	25
5.2.1	Illumination	26
5.2.2	Air circulation	26
5.2.3	Television	27
5.2.4	Refrigeration	28
5.3	Battery study	31
5.4	PV positioning	35
6	Environmental impact	38
6.1	Materials involved in a solar panel	38
6.2	Manufacturing Pollution	39
6.3	Visual impact	39
6.4	PV life-cycle	40
7	Budget	41
	Conclusions	42
	Acknowledgement	44
	Bibliography	45
	Annexes	47

List of Figures

1	Microgrid representation with generation, loads and batteries [2]	6
2	SolBox [2]	7
3	First model of the microgrid [3]	9
4	Second model of the microgrid [3]	10
5	Interconnections for the study [3]	11
6	Converter-less topology scheme [3]	12
7	Converter in PV scheme [3]	12
8	Converter connected to the battery scheme [3]	12
9	Converters connected to battery and PV [3]	13
10	SolShare idea of sharing energy [2]	14
11	New scheme for one household	15
12	First approach of the new grid (only two houses)	16
13	Final grid (only two houses)	16
14	Northon equivalent for the final grid	16
15	Converter-less topology scheme	17
16	Converters connected to each PV topology	18
17	Converters connected to batteries topology	19
18	Converters connected to PV and batteries topology	20
19	Grid scheme with full generation and full load in all panels	22
20	Scheme with full generation and full load except in one panel	22
21	Same scheme once the household battery is empty	23
22	Power simulation during one day	24
23	Picture of a LED used in vans [12]	26
24	Twenty-four hours demand profile related to illumination	26
25	Picture of a BestCool fan, model HX-T305 [13]	27
26	Twenty-four hours demand profile related to air circulation	27
27	15 inches 12 V DC television from a Chinese brand [15]	28
28	Twenty-four hours demand profile related to illumination	28
29	Picture of a 32 W portable fridge [14]	29
30	Twenty-four hours demand profile related to illumination	29
31	Twenty-four hours demand profile	30
32	Precipitation during the year in mm	31
33	Mean temperature evolution [16]	31
34	Generation curve for the 23rd of February	31
35	Generation curve for the 1st of August	31
36	Two cycles of the total battery capacity simulation	33
37	Two cycles of the total battery capacity simulation with the battery upgrade to 80 Ah	33
38	Two cycles of the total battery capacity simulation	34
39	Continuous-time state of charge during 8 days in June (6 extra panels)	35
40	State of Charge during one week (June)	35
41	Same state of charge with distributed power (June)	35
42	State of Charge during one week (August)	36
43	Same state of charge with distributed power (August)	36
44	State of Charge during one week with PV and battery converters (June)	36
45	Same state of charge with PV converters (June)	36
46	State of Charge during one week with PV and battery converters(August)	37

47 Same state of charge with PV converters 37

48 Continuous-time battery state of charge during dry season (8 days in February) . 37

49 Materials in a Sillicon Solar panel [11] 38

50 Matlab code iterative program 48

51 Each Tier characteristics according to World Bank Group 50

List of Tables

1	Solar panel parameters used in the study [6]	10
2	Converter-less first approach	17
3	Converter-less second approach	18
4	Converter connected to PV first approach	19
5	Converter connected to PV second approach	19
6	Converter connected to batteries first approach	20
7	Converter connected to batteries second approach	20
8	Converter connected to batteries and PV first approach	21
9	Converter connected to batteries and PV second approach	21
10	Budget	41

1 Preface

1.1 Renewable energies in the world

The world is experiencing a change in their way of obtaining energy. New technologies have brought with them solutions to one of the biggest problems of humanity: climate change. While centralized methods with huge power plants have become out-dated, renewable energies have started to break into the system.

Solar energy is the source that has grown the most, doubling its installed power in two years. Technical improvements have led to a cost reduction and a productivity increase. Although some countries refuse to accept the irruption of clean energies, others as India and China are strongly investing in this field. The United Arab Emirates is targeting half of its power consumption with clean energy by 2050, as Morocco plan to do so by 2030 [1].

Nevertheless, developing countries present suitable characteristics to broaden solar power supplies as the public infrastructure has not reached the whole population. There's room for the implementation of decentralized power, mostly in off-grid rural zones.

Countries like Bangladesh have 17 million homes without electricity connection. Three millions rely on solar energy, but figures keep growing and growing. Here is where some companies have found a need to fulfill, as the startup SolShare [2].

1.2 Electrification process in Bangladesh

SolShare Ltd. is only an example of an startup that aims to provide a network that shares energy between members of a microgrid in Bangladesh. They install a grid consisting of a group of households with solar panels and batteries in rural zones where there's no electricity available. Some of the members of the grid would have the role of producer, consumer or pronsumer (which means both of them), meaning that some of them will only be able to buy energy.



Figure 1: Microgrid representation with generation, loads and batteries [2]

As mentioned before, microgrids are a clear example of a decentralized power supply, hereby the advantages. First of all, efficiency increases as the energy is produced closer to the consumer and hence, the energy lost due to transportation is lower. Secondly, it provides modularity as it doesn't rely on one large and single supply. If a solar panel stops working, energy can be obtained from another supply. Moreover, this new topology is based on renewable energies, so they're environmentally friendly. Lastly, there's a reliability and economic factor, as the irruption of solar technologies is lowering the prices of its energy, being competitive in the market in the near future.

SolShare Ltd. is also applying an innovative concept: the smart management of the microgrid. Basically, it consists on the regulation of demand and generation, in order to obtain a general benefit in terms of efficiency. Current centralized grids have only one direction of flow (from Power Centrals to your house plug). This new approach is completely different, as the flow is bidirectional. As the power is decentralized, there's an interaction between the owner of a power panel and the grid. The owner has the ability to sell the energy if needed.

It's also remarkable that useful information will be provided to the user. For example, it may prevent you from using the washing machine in a cloudy day. Nevertheless, this model has a lot of challenges to overcome, including a large investment in renewable energies, evolution in storage technology, etc.

The smart distribution of energy in Bangladesh is possible thanks to SolBox (see Figure 2) , SolWeb and SolApp. With the help of these tools, the user can sell or buy energy depending on their needs. During a peak production hour with low load charge, the owner might decide to sell this excess of energy to the microgrid market, while another user might buy it.



Figure 2: SolBox [2]

Until now, SolShare has implemented 48000 Wp in PV capacity and has saved 4970 kg of CO_2 per year.

2 Introduction

2.1 Objectives

At this moment, a lot of companies are trying to fulfill the electrical needs of rural areas in Bangladesh. This regions doesn't have access to the AC grid and they're installing renewable energies in order to solve this issue, mostly solar. There are a lot of models that help to size and perform calculations with electrical systems beforehand. In addition, a MATLAB code has been created by some engineers in Universitat Politècnica de Catalunya for this purpose.

The main goal of this report is to reanalyze these models in order to improve them, using new and more realistic connections between the basic elements of the grid: solar panels, batteries and loads. In order to achieve this goal, several milestones are detailed below:

1. To understand the current context in a developing country as Bangladesh, focusing on the electrification process and how companies are dealing with this opportunity.
2. To use with flexibility the existing MATLAB Code. Having a good idea about the previous work is essential to make changes and see where the blind spots are located.
3. To change the grid modelling for a more realistic one, based on the following idea: one household possesses one battery, one solar panel and several loads.
4. To compare the results of the new model with the centralized model
5. To cope with the near future needs of the farmers in Bangladesh realizing a deeper study of the energetic demand.
6. To resize the system in order to fulfill the new demand paying attention to the battery capacity and the PV production.
7. To do research and have an idea of the environmental impact of solar energy, especially the consequences of the solar panels used in this report.

2.2 Scope of the project

As briefly mentioned before, this projects is focused on the adaptation of an existing model taking into consideration the actual installation layout. Then, comparing the results with the ones obtained before and also go deeper in the demand needs and, consequently, resize the system. It's out of scope the transitory analysis as all the calculations are done assuming steady-state. Also an economic side will not be discussed deeply. It's clear that some findings and decisions are highly related to it, but only a generalist approach will be done.

The environmental impact aims to frame and give an insight of the consequences (sometimes not considered) of the use of solar energy. Nevertheless, studying the energy required to create panels and the methods to recycle them are not examined in depth.

3 Previous work done

3.1 Design of a low voltage DC microgrid using Matlab

The contact between the startup SolShare and UPC's energy department started more than one year ago. A project started by two MsC students aimed to use the technical knowledge of the department in order to perform different type of studies of the current microgrids in Bangladesh.

In that sense, the study had the main objective of setting different scenarios, modelling the electric circuit of the grid and using MATLAB code to calculate different results (with the use of converters in several parts of the circuit). More details of the previous project will be detailed in the following sections.

3.2 Context and objectives

The main objective of the previous project was to automate the designing process of a DC microgrid based on renewable energies. Moreover, it also aimed to collaborate with SolShare in the building of this new technology. Note also that in this case, location is essential. First of all, Bangladesh is a developing country where electricity is not available everywhere. Secondly, these renewable system are being installed in rural off-grid zones, where no AC connection is accessible. On top of that, it needs to be simple, reliable and cost-effective [3].

3.3 Modelling

The model of the circuit can be divided in three different elements: generation (solar panels), loads and storage (batteries). This elements are interconnected with cables which are represented as resistances. In the previous existing model, generation is connected independently from the loads and there's only one bank of batteries.

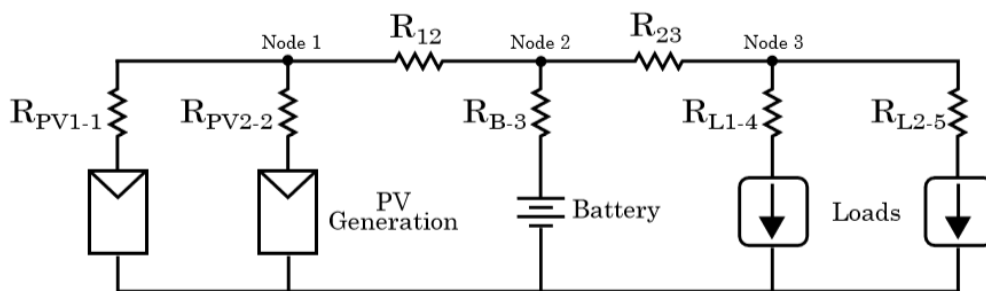


Figure 3: First model of the microgrid [3]

As seen in Figure 3, the grid can be extended as needed. Solar panels and loads can be added depending on the number of households. Then, in order to solve the circuit, all the elements are changed for its Norton equivalent as a current source.

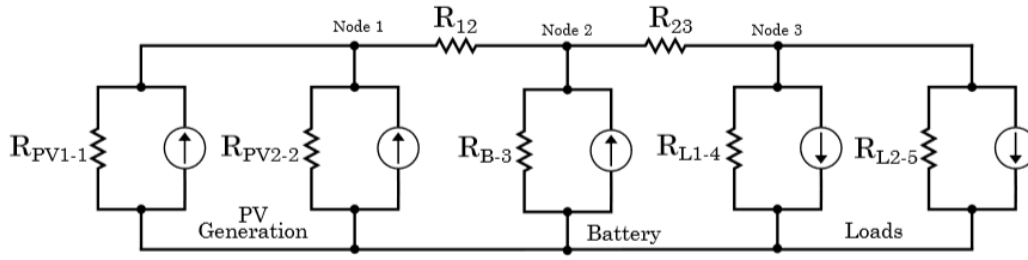


Figure 4: Second model of the microgrid [3]

The calculus of the circuit uses the nodal method, using an admittance matrix Y and following the equation $I = YV$, where V is the nodal voltage vector and I is the nodal current vector. More information about the details of the resolution process are shown in Annex I. Newton's iteration method is used to solve all the equations of the system. Solar panels curve is modelled with the following equations:

$$I = I_L - I_0 \left(\exp \frac{q(V + IR_s)}{nkT} - 1 \right) - \frac{V + IR_s}{R_{SH}} \quad (1)$$

$$I_L = (G/G_{ref}) I_{Lref} (1 + \alpha \times (T - T_{ref})) \quad (2)$$

where V is the output voltage, I is the output current, I_0 is the diode saturation current, I_L are the photo-voltaic current, R_s is the series resistance, R_{SH} is the shunt resistance, G is the solar irradiation, n is the diode quality factor, q is the magnitude of charge carried by an electron, k is the Boltzmann constant, T is the cell temperature and α is the Temperature coefficient. On the other hand, the loads are voltage sources that consume a constant power.

Parameters	Value	Units
I_{SCref}	1.45	A
V_{oc}	22.2	V
R_s	1.0394	ω
R_{SH}	2177.3561	ω
G_{ref}	1000	W/m ²
n	1.3	-
q	1.6022e-19	C
k	1.3806e-23	J/K
T_{ref}	298.15	K
α	0.0048	C ⁻¹
N_{cell}	36	-
I_{Pmax}	1.37	A

Table 1: Solar panel parameters used in the study [6]

3.4 Topologies

Although the size of the grid can be modified, the study was made with 6 houses and, as we can see in Figure 5, there are two branches of cables (one for generation and the other for loads)

and one bank of batteries.

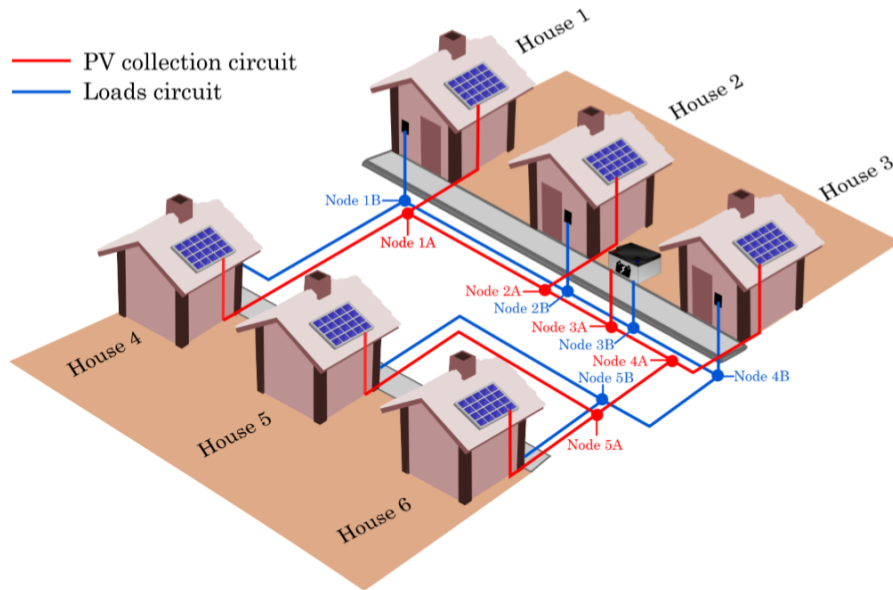


Figure 5: Interconnections for the study [3]

Therefore, four different configurations were treated: converter-less, converter connected to each PV, converter connected to the battery and converter in both PV and battery. Nevertheless, they all have in common the following assumptions:

- All the PV panels are subjected to the same conditions (same irradiation), so do the loads
- Battery Voltage is defined
- Load Power is defined
- Two different irradiation scenarios: 1000 W/m^2 (day) and 0 (night)
- Two different load consumption scenarios: 50 W and 0
- Nominal grid voltage is 12 V

Converter-less topology

In this first scenario without converters, the load power and battery voltage are both imposed, while the circuit is solved using the I-V curves of the PV model.

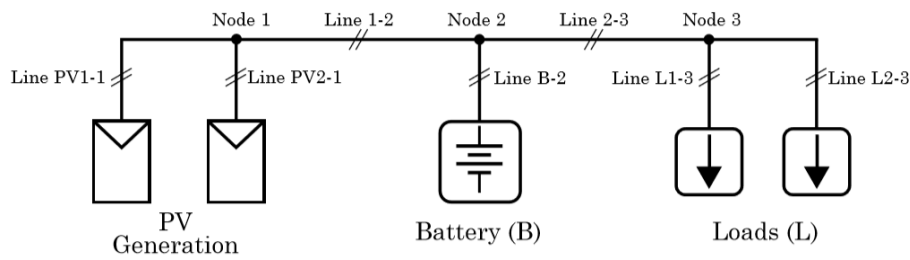


Figure 6: Converter-less topology scheme [3]

Converters connected to solar panels

The second scenario places one converter in each solar panel, forcing them to reach their Maximum Power Point (MPP). Hence, the panel curves are not needed for the calculations. The battery voltage and load power is imposed as in the previous case and the converter losses are neglected.

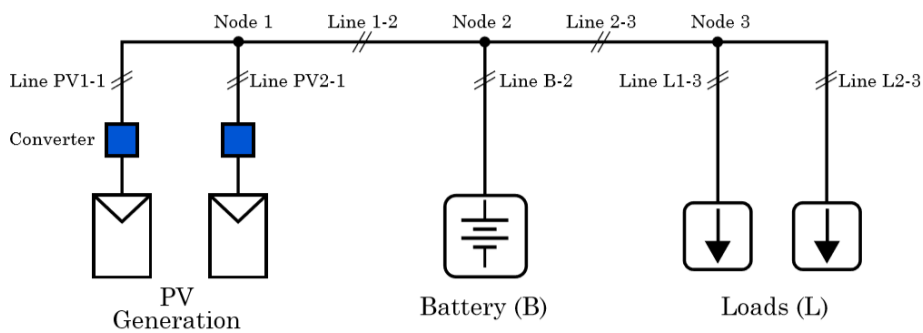


Figure 7: Converter in PV scheme [3]

Converter connected to the battery

The third case is similar to the first one. The battery voltage is optimized. This voltage is fixed until the power flow throughout the battery is minimum.

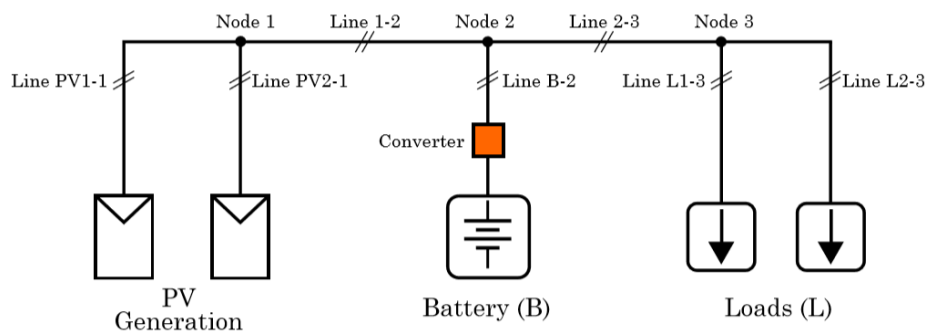


Figure 8: Converter connected to the battery scheme [3]

Converters connected to battery and PV

The last study case will lead the solar panels to their MPP but will also optimize the battery voltage. Nevertheless, this voltage tends to infinity. That's why a maximum load voltage is implemented in order to be realistic and maintain the microgrid voltage close to the nominal value.

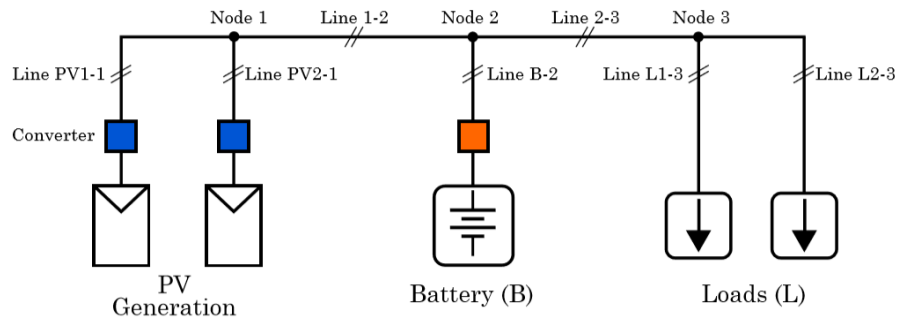


Figure 9: Converters connected to battery and PV [3]

4 Case study

4.1 New modelling

As commented in section 2, the aim of this report is to realize a more realistic approach of a typical renewable energy based microgrid in Bangladesh, specially the ones the startup SolShare is implementing.

In this sense, the previous work has advised an import milestone as it sets perfectly the context and the basis to distribute the elements of the grid. Nevertheless, the real connections between solar panels, loads and batteries differ a little bit from the one's implemented in the first model. Actually, the microgrid will be redistributed and recalculated in order to see if both models are far away from each other.

The new approximation that will be used during all the report considers one household and its integrated parts as one basic element. Therefore, each house will be modelled as a solar panel, a load and a battery connected in parallel. Generation, consumption and storage will not be centralized anymore.

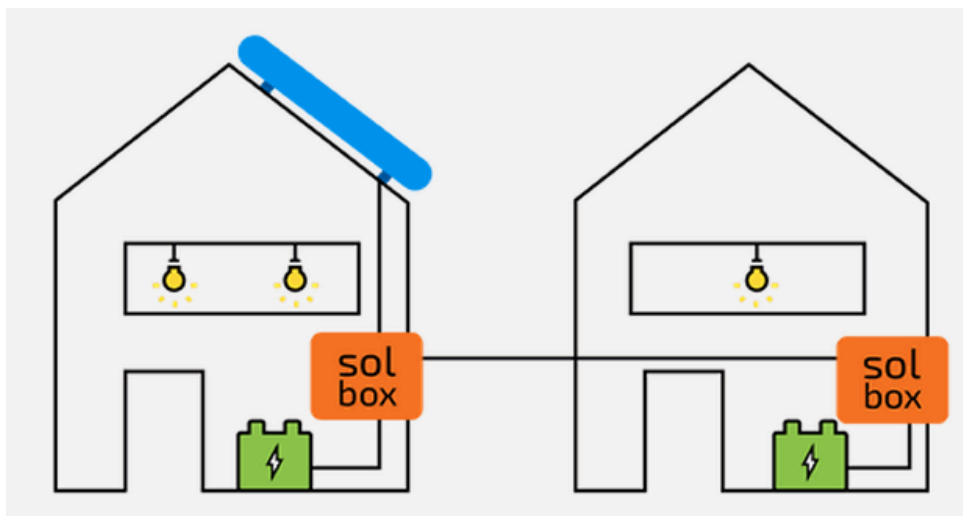


Figure 10: SolShare idea of sharing energy [2]

As seen in the previous picture, not all the houses need to own a solar panel. Nevertheless, in this study all the houses will have one solar panel, one battery and loads. All homes will be bound to the same conditions.

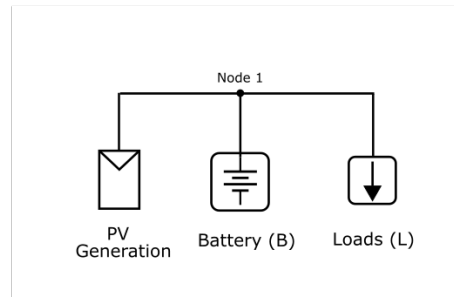


Figure 11: New scheme for one household

Although the concept is quite different from the original, the solving method is not. The scenarios to compare the results are: all the PV subjected to the same irradiation, batteries voltage fixed, load power defined, two irradiation scenarios and two load consumption scenarios.

The circuit scheme will use the same basis as the previous study, using the Norton equivalent to compute the PV generation, the batteries and loads. Despite that, the admittance matrix Y has changed. The MATLAB code can be executed after defining the grid, and the grid is completely defined with two matrixes. The first one computes the distance in meters between nodes. This will be used to calculate the resistance of cables between elements. Some extra nodes have been created in order to have one current source between all the nodes and the reference nodes (see difference between Figure 12 and Figure 13). In order to do that, it's needed to add a really low resistance between two points which were only one at first. Hence, the distance of cable is different depending on the installation. This parameters can be changed when the matrix is defined. For the calculation in this section, the next approximations have been done: 10 meters of cable between houses ($R_{j,j+1}$), 5 meters from the PV until the central node of a house (R_{PVi}) and 1 m between each load (R_{Li}) or battery R_{Bi} until the central node of a house. This central node is the one that connects one house to the next one. As said before, more nodes have been created with a distance of 0.01 meters between the virtual new nodes ($R_{j,j+1}$), where i is the house number and j is the node number.

The second matrix is a $1 \times n$ matrix with 1, -1 or 0. If there's a solar panel between the node n and reference node, this vector position will have a 1, a 0 for the battery and a -1 for a load (Annex II). Apart from these matrix variations, more code modifications were necessary as the implementation of several batteries presented problems at the beginning.

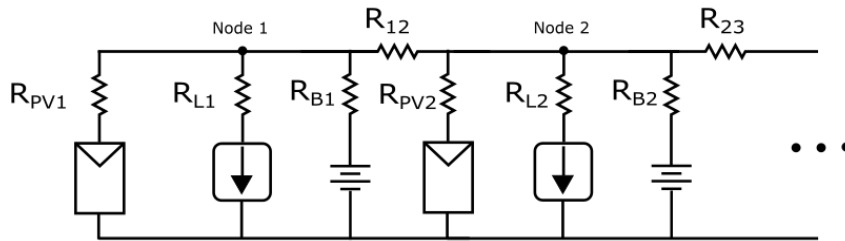


Figure 12: First approach of the new grid (only two houses)

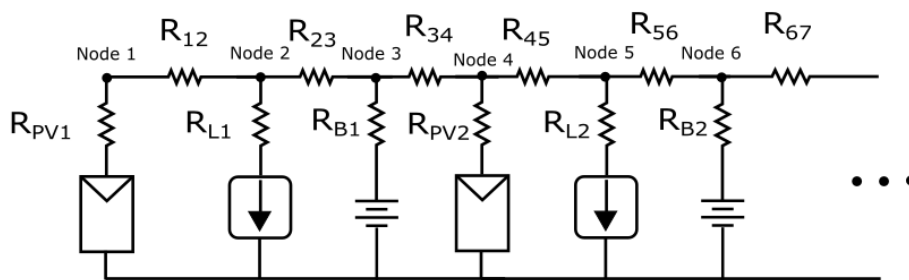


Figure 13: Final grid (only two houses)

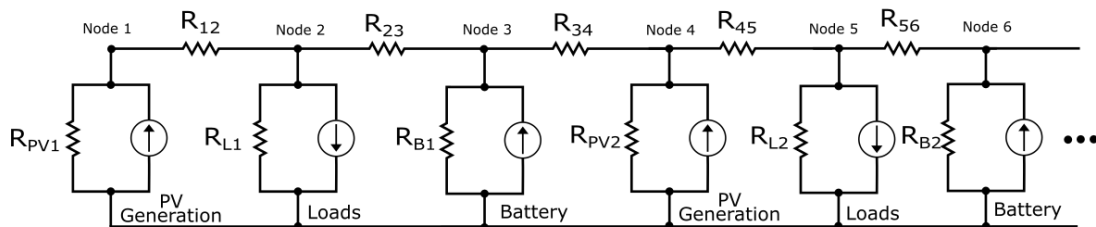


Figure 14: Northon equivalent for the final grid

Note that some nodes and resistances have changed their name. Nevertheless, the final and right notation is shown in Figure 14. Thanks to these matrix and using the PV characteristics, the programs will solve the equations using the Newton's iterative Method [4].

4.2 Converter-less topology

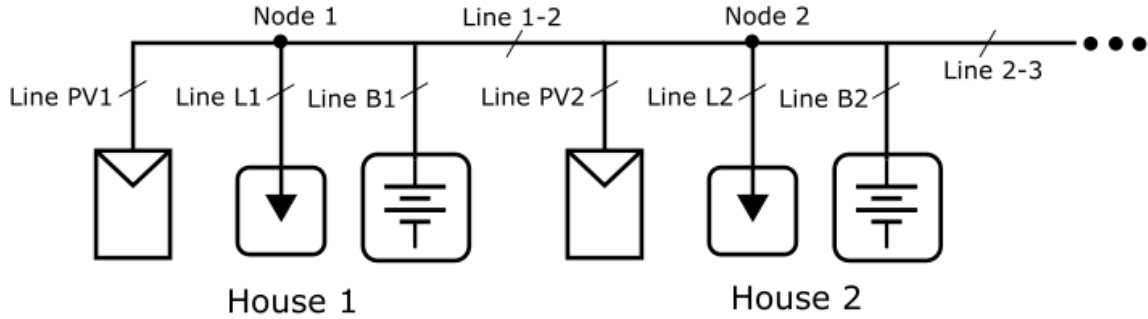


Figure 15: Converter-less topology scheme

This first section will analyse the results obtained from the new grid scheme, without converters connected to the system.

On the one hand, it's remarkable to say that the main difference with the first approach is the use of several batteries. This fact reduces considerably the maximum current of the grid because, in the previous approach, this current was maximum in the battery and now it has been divided. Hence, the grid losses are lower since the Joule effect power has been reduced (this happens not only in this topology but in all of them).

On the other hand, it's true that depending on the grid the losses might be much higher, especially if the cable between the battery and loads is long (as the current flowing through these elements is higher). So, in conclusion, having a good understanding of the elements of the grid, the position of the battery can become crucial for a better performance of the grid.

Then, it can be stated that this topology in particular presents the same generation (as the number of houses and therefore solar panels is the same), but the reduction of losses is reflected in more energy flowing to the battery, as seen in Tables 2 and 3.

Parameter Name	G=1000 W/m ²		G = 0 W/m ²		G=1000 W/m ²	
	P _L = 50W		P _L = 50W		P _L = 0W	
	Sum	Mean	Sum	Mean	Sum	Mean
P _{pv}	104.06 W	17.34 W	0 W	0 W	108.24 W	18.24 W
P _{load}	-300 W	-50 W	-300 W	-50 W	0 W	0 W
P _{bat}	240.7 W	240.7 W	350.66 W	350.66 W	-103.43 W	-103.43 W
I _{max}	20.06 A	-	29.22 A	-	8.619 A	-
P _{loss}	44.76 W	-	50.66 W	-	4.33 W	-

Table 2: Converter-less first approach

Parameter Name	$G=1000 \text{ W/m}^2$		$G = 0 \text{ W/m}^2$		$G=1000 \text{ W/m}^2$	
	$P_L = 50W$		$P_L = 50W$		$P_L = 0W$	
	Sum	Mean	Sum	Mean	Sum	Mean
P_{pv}	104.28 W	17.38W	0 W	0 W	104.59 W	17.432 W
P_{load}	-300 W	-50 W	-300 W	-50 W	0 W	0 W
P_{bat}	197.55 W	32.924 W	301.81 W	50.302 W	-104.84 W	-104.84 W
I_{max}	4.1874 A	-	4.1951 W	-	1.4584 A	-
P_{loss}	1.8253 W	-	1.8118 W	-	0.64553 W	-

Table 3: Converter-less second approach

4.3 Converter connected to PV topology

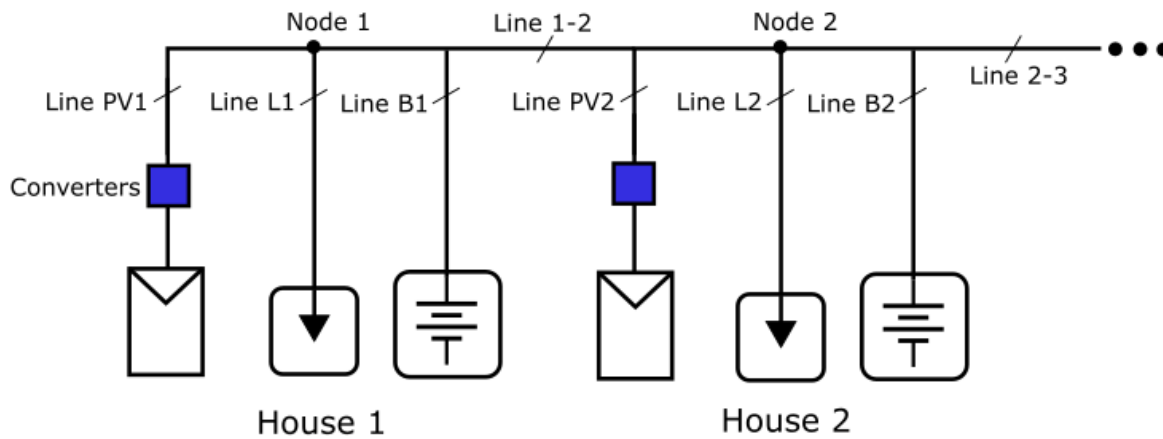


Figure 16: Converters connected to each PV topology

The second section adds one converter for each PV solar panel. A Maximum Power Point control is considered, leading the generation to the maximum. Converter losses are neglected.

Same as in the previous section, generation remains the same between the two different models. Also the maximum current and the power losses have been reduced. In a full load and full irradiation scenario, the battery would absorb 160 W against the 200 W of the first model, which implies a reduction of the 20%. The reveals of these simulations are shown in Tables 4 and 5.

Parameter Name	$G=1000 \text{ W/m}^2$ $P_L = 50W$		$G = 1000 \text{ W/m}^2$ $P_L = 0W$	
	Sum	Mean	Sum	Mean
P_{pv}	141.57 W	23.6 W	141.57 W	23.6 W
P_{load}	-300 W	-50 W	0 W	0 W
P_{bat}	203.22 W	203.22 W	-134.32 W	-134.32 W
I_{max}	16.94 A	-	11.19 A	-
P_{loss}	44.79 W	-	7.25 W	-

Table 4: Converter connected to PV first approach

Parameter Name	$G=1000 \text{ W/m}^2$ $P_L = 50W$		$G = 1000 \text{ W/m}^2$ $P_L = 0W$	
	Sum	Mean	Sum	Mean
P_{pv}	141.57 W	23.6 W	141.57 W	23.6 W
P_{load}	-300 W	-50 W	0 W	0 W
P_{bat}	160.57 W	26.761 W	-140.4	-23.399 W
I_{max}	4.1859 A	-	1.953 A	-
P_{loss}	2.1396 W	-	1.1742 W	-

Table 5: Converter connected to PV second approach

4.4 Converter connected to batteries topology

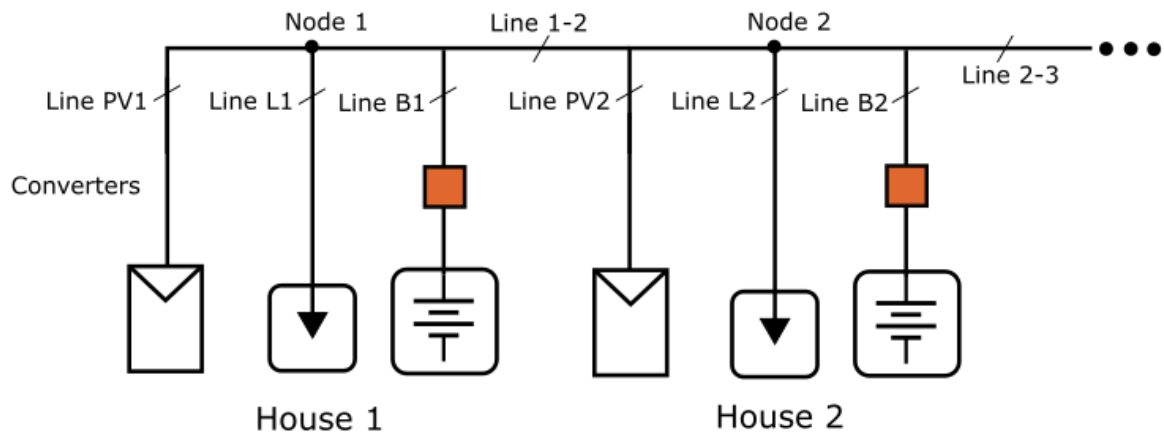


Figure 17: Converters connected to batteries topology

Unlike the previous sections, the generation power has been reduced compared to the old model. Despite that, the reduction is really low and still the battery power obtains better results.

The converter controls the battery voltage, also optimizing it in order to minimize the power exchange.

The other parameters (power losses and maximum current) have also been reduced compared to the first model. The reveals of these simulations are shown in Tables 6 and 7.

Parameter Name	G=1000 W/m ² P _L = 50W		G = 0 W/m ² P _L = 50W		G=1000 W/m ² P _L = 0W	
	Sum	Mean	Sum	Mean	Sum	Mean
P _{pv}	134.15 W	22.36 W	0 W	0 W	131.33 W	21.88 W
P _{load}	-300 W	-50 W	-300 W	-50 W	0 W	0 W
P _{bat}	189.06 W	189.06 W	325.01 W	325.01 W	-127.00 W	-127.00 W
I _{max}	12.11 A	-	20.64 A	-	8.55 A	-
P _{loss}	23.21 W	-	25.02 W	-	4.26 W	-

Table 6: Converter connected to batteries first approach

Parameter Name	G=1000 W/m ² P _L = 50W		G = 0 W/m ² P _L = 50W		G=1000 W/m ² P _L = 0W	
	Sum	Mean	Sum	Mean	Sum	Mean
P _{pv}	129.38 W	21.563 W	0 W	0 W	129.23 W	21.539 W
P _{load}	-300 W	-50 W	-300 W	-50 W	0	0
P _{bat}	171.91 W	28.651 W	301.15 W	50.191W	-128.41 W	-21.402 W
I _{max}	3.3355 A	-	3.3375 A	-	1.4303 A	-
P _{loss}	1.2844 W	-	1.1468 W	-	0.63132 W	-

Table 7: Converter connected to batteries second approach

4.5 Converter connected to batteries and PV topology

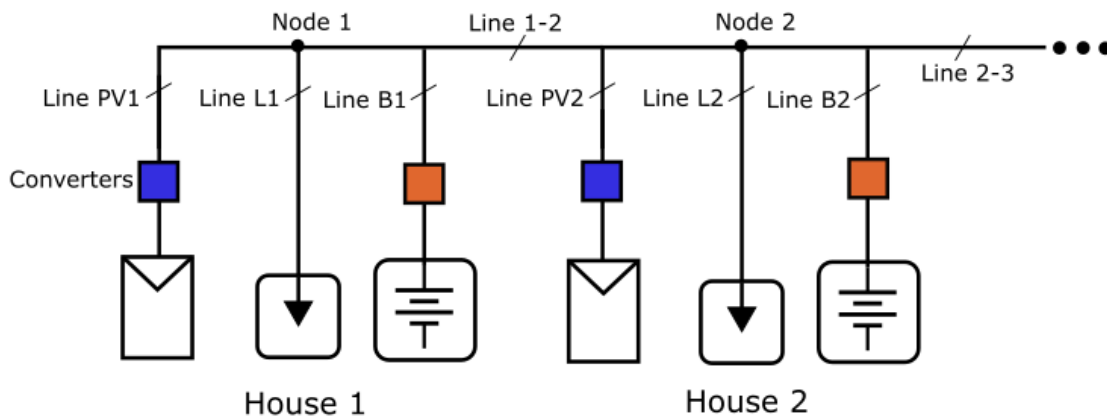


Figure 18: Converters connected to PV and batteries topology

Adding converters to both batteries and solar panels provides the maximum power production but also has into account the power losses. In this sense, production remains the same as in the second section (converters connected only to PV) but losses are reduced in almost a fifty per cent in the full load and full irradiation scenario.

Compared to the first model, the tendency remains the same (losses and maximum current have been reduced). Voltage limit has been fixed at 15 V (25% higher than the nominal voltage). The reveals of these simulations are shown in Tables 8 and 9.

Parameter Name	$G=1000 \text{ W/m}^2$ $P_L = 50W$		$G = 1000 \text{ W/m}^2$ $P_L = 0W$	
	Sum	Mean	Sum	Mean
P_{pv}	141.57 W	23.6 W	141.57 W	23.6 W
P_{load}	-300 W	-50 W	0 W	0 W
P_{bat}	181.77 W	181.77 W	-136.65 W	-136.65 W
I_{max}	11.65 A	-	9.21 A	-
P_{loss}	23.34 W	-	4.92 W	-

Table 8: Converter connected to batteries and PV first approach

Parameter Name	$G=1000 \text{ W/m}^2$ $P_L = 50W$		$G = 1000 \text{ W/m}^2$ $P_L = 0W$	
	Sum	Mean	Sum	Mean
P_{pv}	141.57 W	23.6 W	141.57 W	23.6 W
P_{load}	-300 W	-50 W	0 W	0 W
P_{bat}	159.79 W	26.632 W	-140.81	-23.469 W
I_{max}	3.3342 A	-	1.5691 A	-
P_{loss}	1.361 W	-	0.758 W	-

Table 9: Converter connected to batteries and PV second approach

4.6 Shadow study

Another interesting situation occurs when a solar panel is in the shade while the others are generating at MPP. This incident is willing to happen because of a tree shadow or simply the appearance of a cloud.

Scenario model is the following: five panels generating at MPP while one panel is producing no power. Load is fixed at 50 W in all the households (including the one without generation). Topology with converters everywhere is considered.

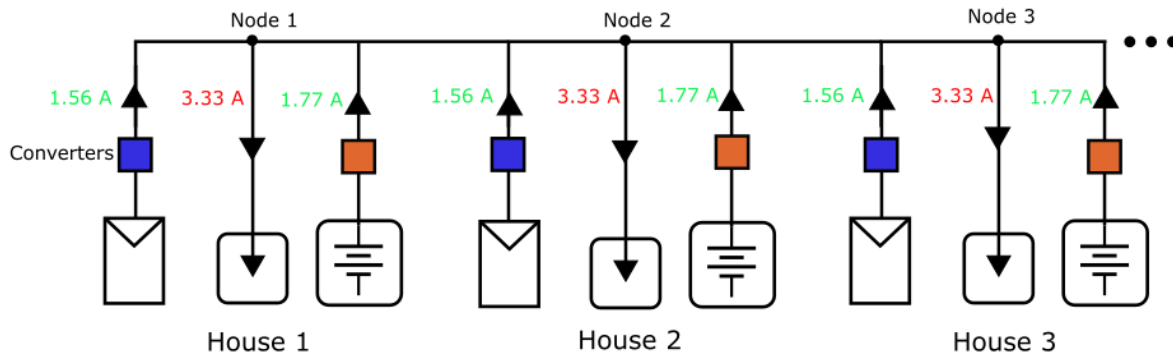


Figure 19: Grid scheme with full generation and full load in all panels

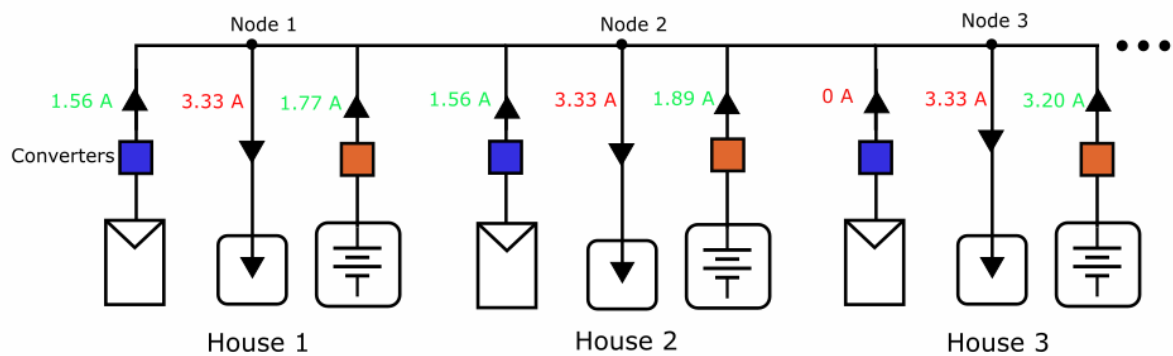


Figure 20: Scheme with full generation and full load except in one panel

Until now, the grid was working in a symmetric way. Energy consumed in one household comes mostly from the PV installed in this household and also its battery. If this energy supply does not fulfill the demand, more energy flows from other households nearby. Nevertheless, this power flow is less efficient because the transportation losses are higher. So in the first figure (Figure 19), it can be seen the usual behaviour of the grid with all the households bound to the same conditions ($P_{loss} = 1.33 \text{ W}$).

Afterwards, generation in one household stops. Then, the battery of the same household needs to operate at a higher power level to solve this lack of energy. During this process, the energy of its own household is 'cheaper' than the one coming from others (Figure 19). In addition power losses remain almost the same ($P_{loss} = 1.34 \text{ W}$).

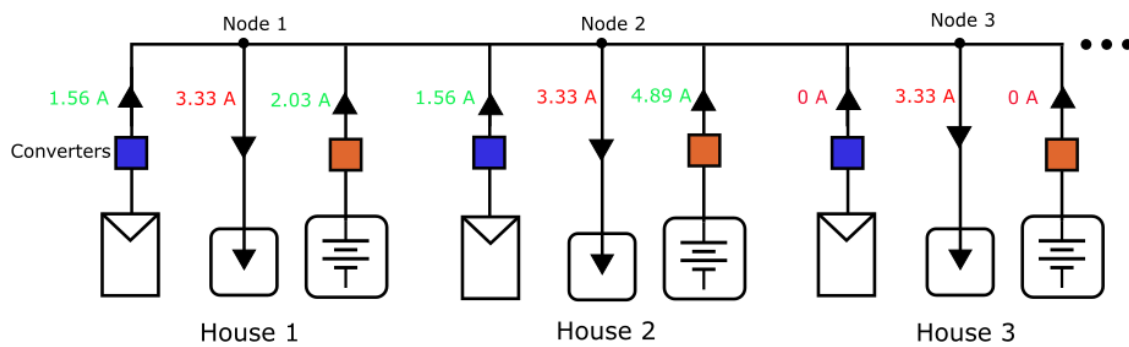


Figure 21: Same scheme once the household battery is empty

As this single battery is using extra power, it will drain faster and then energy will be needed from other neighbours (Figure 21). If this happens, power losses are doubled during this exchange of energy ($P_{loss} = 2.66 \text{ W}$). These numbers are still low compared to the amount of power produced but depending on the grid they might be taken into consideration.

5 Time-domain simulation

5.1 Starting point

Apart from analysing different steady-state scenarios, it is important to study the behaviour of the grid during a period of time. Depending on the generation power and more importantly its profile the dimensions of the grid might need to be adapted.

Obviously, the demand profile is also essential in order to understand the needs, the exact time when the greater part of the consumption occurs and consequently how to implement the correct amount of PV panels and batteries.

During the old study, a twenty-four hour simulation was done, plotting the load power, the generation power and the power flowing to the battery as seen in Figure 22. This simulation uses the Steady-State analysis hourly. The demand profile data was provided by SolShare. In order to obtain the generation curve, in site weather data was used. More information about the weather conditions in Bangladesh are commented in the following section. Moreover, the battery profile is obtained from the MATLAB code. Each hour, depending on the generation, loads and losses, more or less power flow will be absorbed.

It can be concluded that the power stored in the batteries is able to fulfill the demand. This curve corresponds to a day in February and with converters everywhere. But there are several points to discuss, such as the capacity of the batteries or how are the generation and load profile computed.

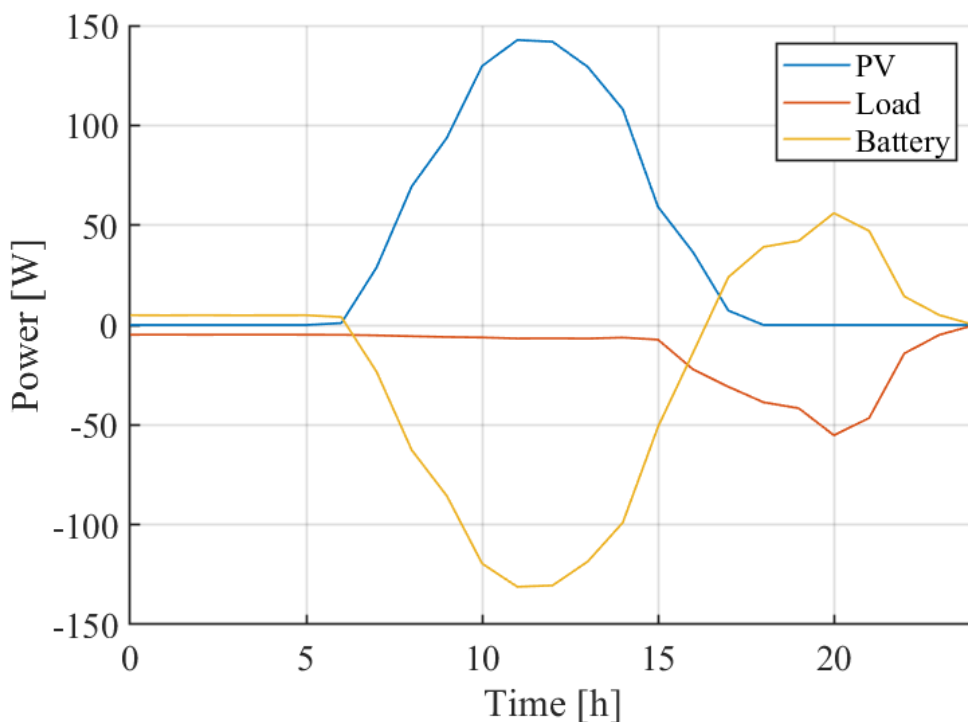


Figure 22: Power simulation during one day

First of all, the equipment parameters in the first approach were taken from the ones currently used in Bangladesh microgrids. For example, battery capacity is 50 A·h as these are the ones installed there.

Secondly, solar panels characteristics are the same as the ones used in the previous sections [6]. Nevertheless, power generation depends on the temperature and the irradiation and therefore, the hourly temperature and irradiation in Dhaka (Bangladesh's capital) were imposed¹. The demand profile will be discussed next.

Using the MATLAB code to calculate the steady-state powers hourly and fixing the demand, a time-domain plot as the shown before can be obtained.

5.2 Demand profile

Guessing the power needs of population from a certain region is a critical issue in order to compute the demand profile. There are many factors to consider to obtain reliable results.

Energy access has been commonly measured using only two possible situations: access or no access to the grid. Contrary to that, the World Bank Group has been working in an improved classification that takes other factors into account as quality, reliability, affordability, safety and availability when needed [5]. This indicator is called Multi-Tier Framework, and it goes from Tier 0 (that corresponds to an off-grid situation) to Tier 5 (with minimum 2 kW, 23 hours per day minimum 4 at night, maximum 3 energy disruptions per week...). Further information can be found in Annex III.

Hence, a Tier 2 has been assumed for all the previous sections, which consists in a 4 hours per day electricity connection with a maximum of 50 W per household. In order to draw the first load profile, some data from a PV microgrid company in Bangladesh was used. This data is shown in the last figure and agrees with the Tier 2 constraints. It has a power peak of 9 W per household at 20 hours.

Anyway, this demand could represent only the power of two energy-efficient lamps and mobile charging. Although it still corresponds to a Tier 2 frame, the long term aim of the microgrid is to fulfill people's needs and evolve as far as possible.

Analysing a couple of interviews to local people from the region [2], some important data was obtained. For example, they mostly mention the basic need of lightning and phone charging. But some of them mentioned drinking a glass of cold water after a long workday and a bit of fresh air. Also watching television.

In other words, potentially useful loads are: lighting, a fan, television, a little fridge and mobile charging.

¹These irradiation and temperature values can be obtained from a website that computes these values hourly during a year.

5.2.1 Illumination

First, note that the grid nominal voltage is 12 V. It is a quite common value. Some solar elements are able to operate at values as 12, 24 or 48 V. Secondly, the grid does not have inverters meaning that the system is governed by direct current. A common power value for a energy-efficient lamp using LED technology is 4 W.



Figure 23: Picture of a LED used in vans [12]

The previous picture shows an example of a direct current lamp. Its power load is 4 W and it has an input range from 9 to 30 V. Then, it is something similar to the lamps that can be used in Bangladesh. The load profile related to one household (including two LEDs) is shown in Figure 24. Lastly, the load consumption will be the same for all the households.

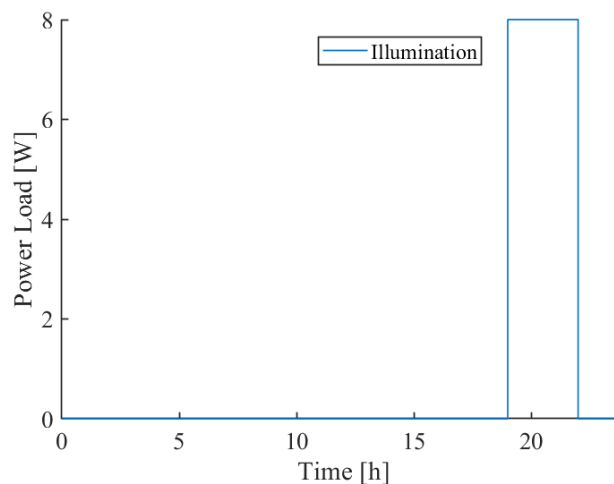


Figure 24: Twenty-four hours demand profile related to illumination

5.2.2 Air circulation

The implementation of a fan in every household is another basic need. During hot season, switching a fan on can make a really big difference. It is also doable as this devices does not consume a lot of power. This 12 V DC fan shown in the following picture consumes only 4 W.



Figure 25: Picture of a BestCool fan, model HX-T305 [13]

Therefore, a probable demand profile approximation can be the one in Figure 25. It would be switched on during lunch time and after work time (4 hours per day approximately).

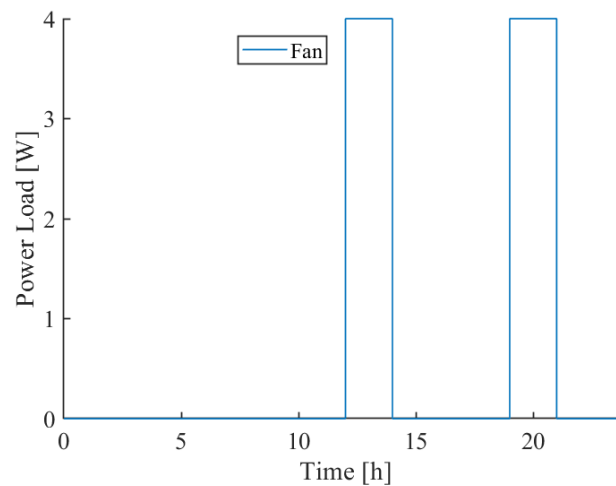


Figure 26: Twenty-four hours demand profile related to air circulation

5.2.3 Television

In order to build the TV profile, 3 hours during night are considered. A DC television of 15 inches as the one in Figure 27 requires a power of 10 W. Taking this into account and considering all the houses with equal load, the profile of one household is finally the one shown in Figure 28.



Figure 27: 15 inches 12 V DC television from a Chinese brand [15]

Bigger televisions were considered up to 40 inches but the power needed exceeded 50 W and therefore were dismissed.

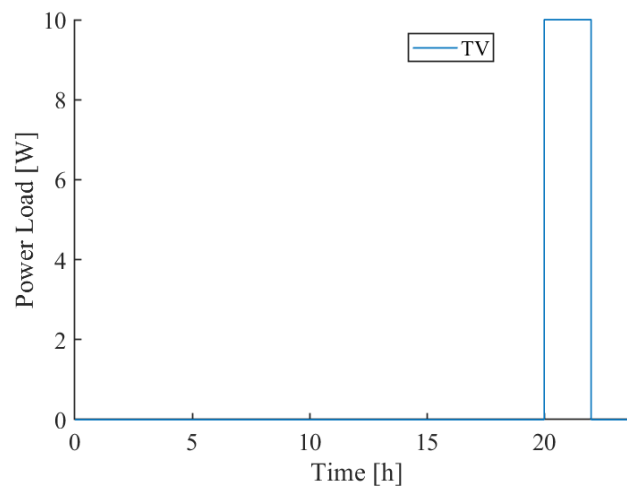


Figure 28: Twenty-four hours demand profile related to illumination

5.2.4 Refrigeration

In one of the interviews to a local farmer in Dhaka [2], he claimed that a cold glass of water after a long workday in the field would be a breathe of relief. It could seem an easy goal at first sight but the power involved in refrigeration is greater than the power consumed by the other devices.

A little fridge can easily consume 50 W. Nevertheless, some of them can reach the value of 35 W. Contrary to the other demand studies, only one household per day will be able to use the fridge in order to reduce the consume. Also only one hour of consumption per day will be assumed. Note that a typical fridge profile is different. It would be constant because, theoretically, it needs to operate during 24 hours. In this case, the purpose of this fridge is only to cool down a glass of water (this is why the profile in Figure 30 is not constant).



Figure 29: Picture of a 32 W portable fridge [14]

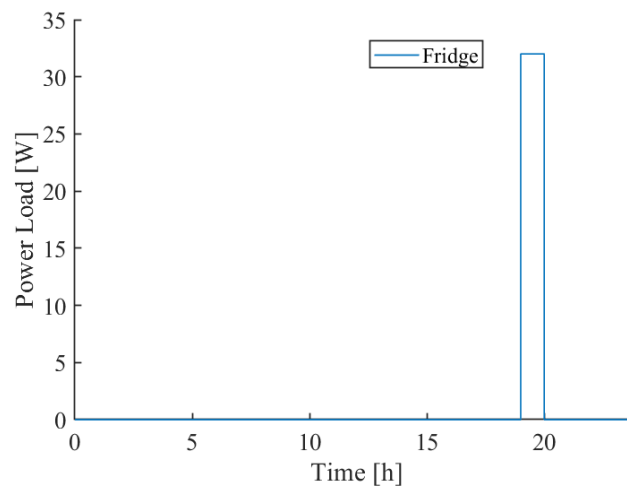


Figure 30: Twenty-four hours demand profile related to illumination

In conclusion, the 6 households microgrid demand has increased substantially with the intention of improving the user possibilities and therefore, his quality of life. Combining all the loads (remembering that the fridge can operate only in one household during one hour per day), the final profile is obtained and showed in Figure 31. There is a peak of 164 W at 20 hours. At that time, generation power is low. Nevertheless, with a good battery sizing and generating with the PV during the day, demand can be fulfilled. It will be analysed in the following section.

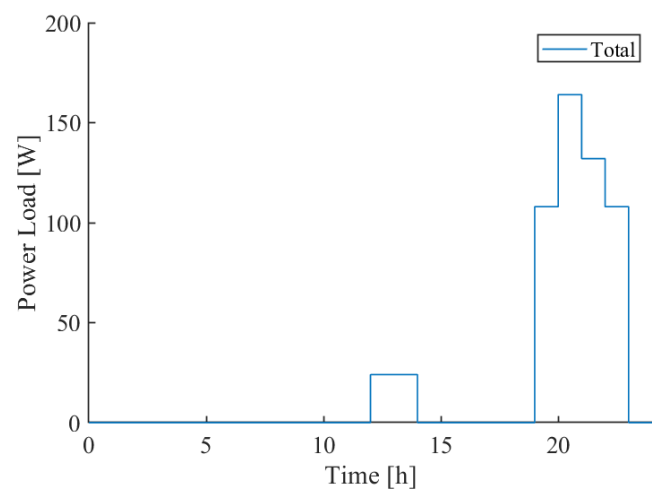


Figure 31: Twenty-four hours demand profile

5.3 Battery study

Once the demand has been defined, it's important to study the weather conditions on site. As mentioned before, hourly irradiation and temperature values are tabulated. But first of all, having an idea of the climate beforehand will help with the data management.

Dhaka has a tropical climate, characterized by only two seasons: dry and wet. The average temperature is 25.9°C. Temperatures are quite stable, varying from 12 until 33°C. On the one hand, wet season or monsoon (mostly during European summer) gathers most of the yearly precipitation. On the other hand, dry season is a little bit colder but the amount of sunlight hours increases as there's no rain [16].

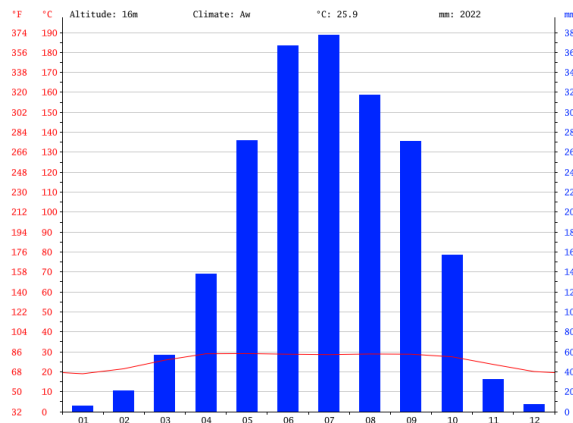


Figure 32: Precipitation during the year in mm

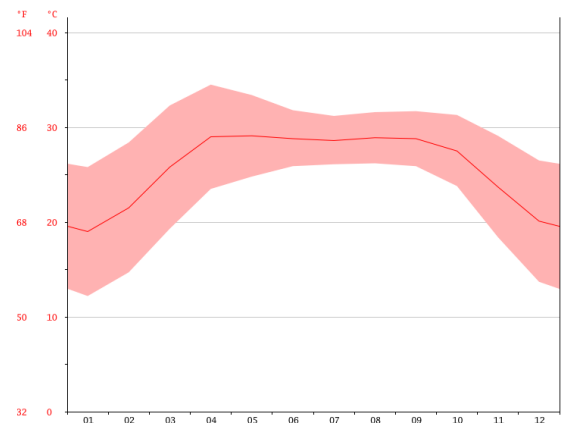


Figure 33: Mean temperature evolution [16]

In order to realize this study, the same day of February will be considered because it represents a typical sunny day during dry season (Figure 34). During the monsoon, the generation curve is irregular and less power is obtained from the PV (Figure 35).

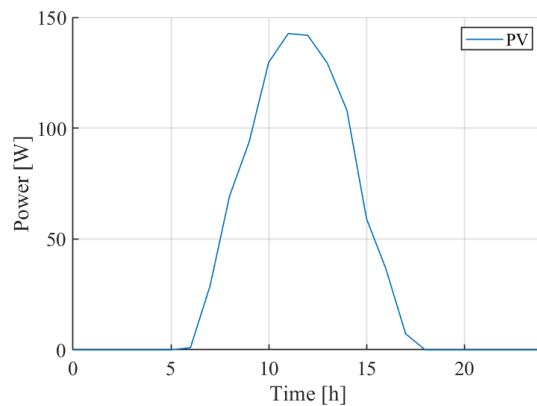


Figure 34: Generation curve for the 23rd of February

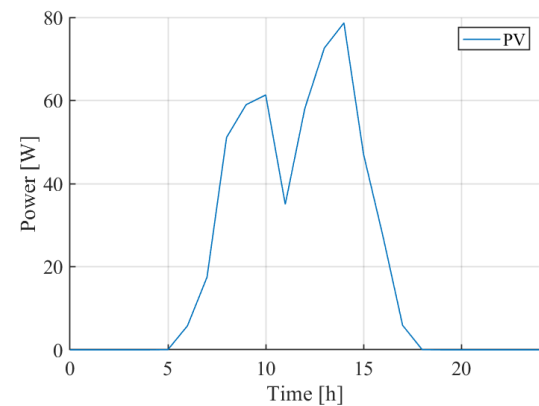


Figure 35: Generation curve for the 1st of August

Monsoon season represents almost half of the year. Although dry season has better conditions for generation, it is important to fulfill the demand the other half of the year too. So, basically, the objective in this sizing is provide an affordable but also reliable source of energy during as much time as possible. Therefore, the priority of this study is sizing the installation based on an average wet week. Nevertheless, it is impossible to pretend to produce the necessary energy in a completely cloudy day.

The sizing method starts with the boundary conditions, considering some assumptions previously used:

- All PV are bound to the same irradiation/temperature conditions
- Loads are considered the same in all the households
- Demand profile remains the same during the whole year
- The grid is formed by only 6 household
- Converters are connected to both PV and battery
- Each battery has a capacity of 50/6 A·h (during the old study the central bank of batteries had a capacity of 50 A·h)
- Nominal grid voltage is 12 V
- All batteries charge and discharge in the same extent
- Initial state of charge of the battery is 33% of its capacity

Battery cycle lasts one day. During the day, PVs charge the battery whether after 17 h the discharge starts (as previously seen in Figure 22). Hence, the first step (as the demand is considered constant) was to analyze how much energy is lost during night in order to have enough battery capacity as it will empty the same every day. The continuous-time analysis of the state of charge will be used for that purpose. The first results can be shown in the following Figure 36.

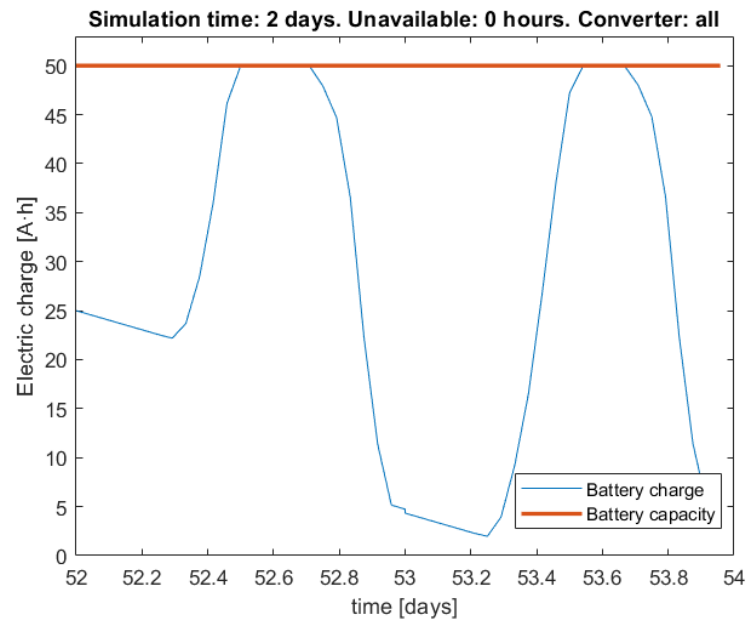


Figure 36: Two cycles of the total battery capacity simulation

This simulation above represents the best case scenario (dry season) with the current generation (6 solar PV) and a total battery capacity of 50 A·h. Battery capacity is clearly not enough as the difference between the peak and the lowest point is more than 50 A·h. Increasing up to 100 A·h, it is seen that during night, the use of energy is approximately 50 A·h. Moreover, battery life considerably decreases if it is discharged until less than 33%. It can be concluded that upgrading the battery capacity in 30 A·h is adequate (see Figure 37 and note that battery capacity is now 80 A·h).

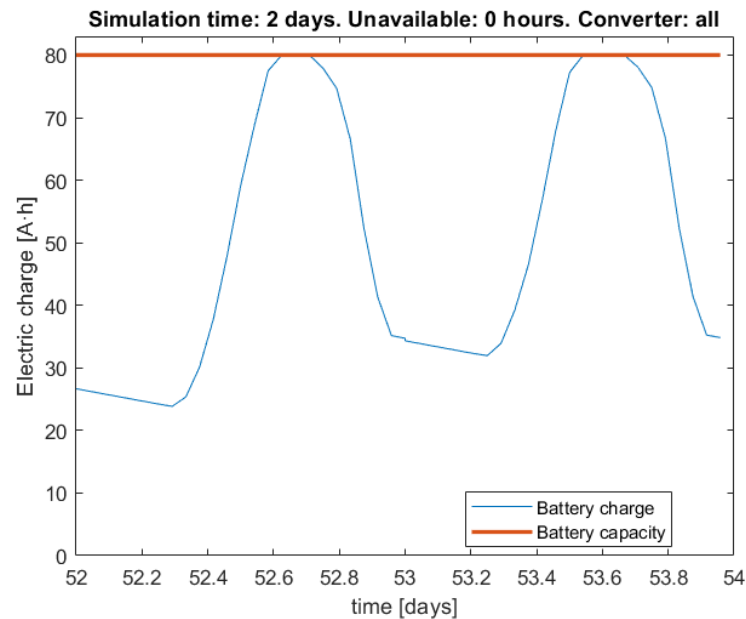


Figure 37: Two cycles of the total battery capacity simulation with the battery upgrade to 80 A·h

In general, increasing the battery capacity is way more expensive than increasing the number of PV panels. It is extremely necessary in this case as most part of the consumption takes place during night. It is also seen that 6 solar panels produce enough energy during dry season.

Next to that, a further study of the wet season grid behaviour needs to be done. Using 8 days in June, the battery state of charge plot shown in Figure 38 reveals that during wet season more generation is necessary.

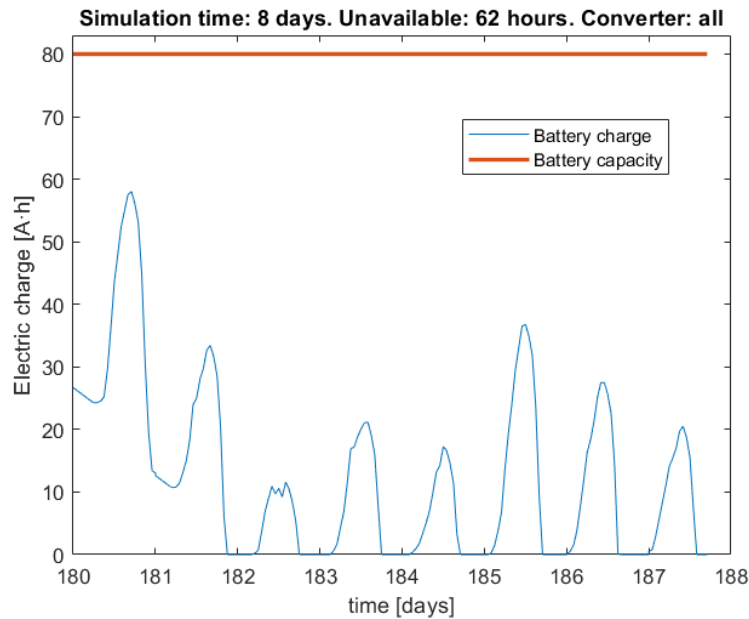


Figure 38: Two cycles of the total battery capacity simulation

So the next step was increasing the PV generation, using the same panel characteristics but increasing the number of them. A first approach implemented a group of panels (12 extra panels) in one end of the grid, reducing the number of active panels until the profile was optimal.

Above six extra panels, the grid is oversized. It fulfills completely the night demand but too much energy is wasted during the day. Increasing the battery capacity is an expensive option and will not help with the proposed demand profile.

Nevertheless, the grid reaches its principal goals with 6 extra panels (see Figure 39): reliability and affordability. Sometimes the state of charge is below the 33% limit. It's impossible to be efficient in a cloudy day as the energy source used relies in the sun. Then it would be naive to realize a grid sizing based on this type of days (as seen in day 182, 183 and 184). In a dark day, consumption must be controlled by the user (as seen in day 182, 183 and 184).

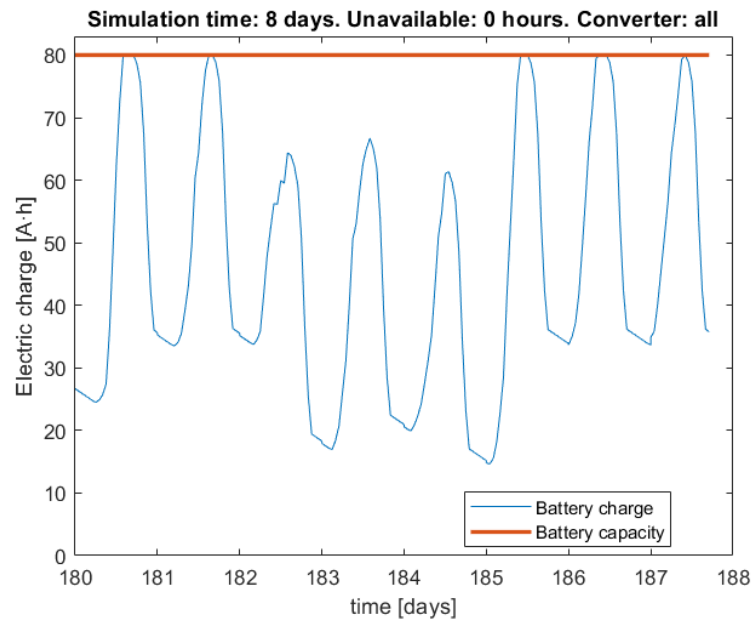


Figure 39: Continuous-time state of charge during 8 days in June (6 extra panels)

5.4 PV positioning

Although using a centralized extra power can help increase the generation, there are other alternatives that might be more energy-efficient. In this section, another PV topology will be compared to the one proposed in the previous section.

The new topology considered here consists on the following: connecting each extra panel in parallel to one already existent. This way, power produced is distributed and theoretically, with equal demand in all the households, less transportation will be needed.

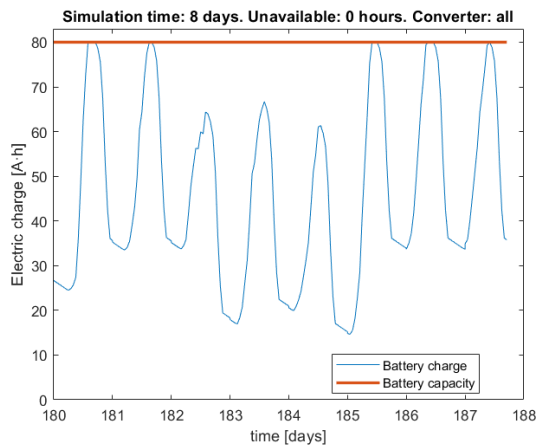


Figure 40: State of Charge during one week (June)

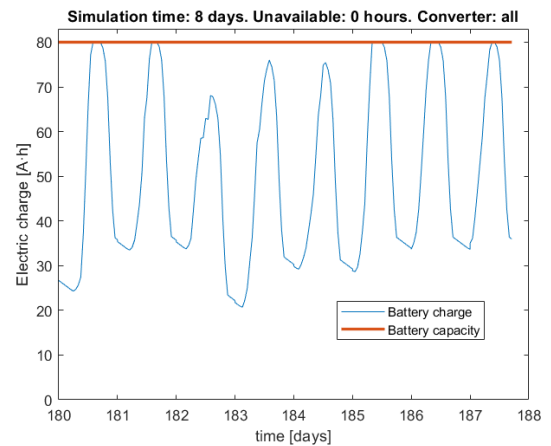


Figure 41: Same state of charge with distributed power (June)

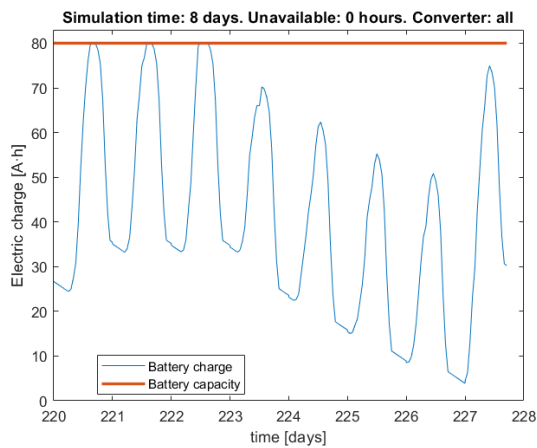


Figure 42: State of Charge during one week (August)

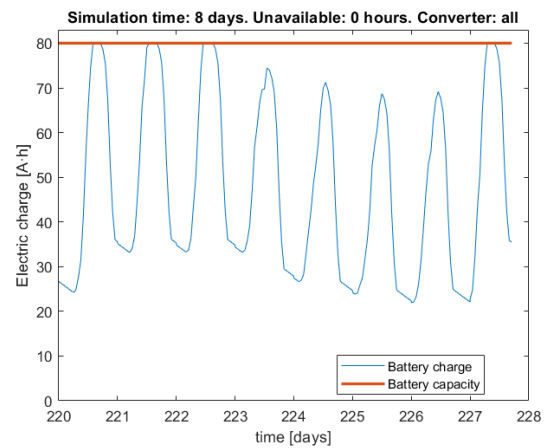


Figure 43: Same state of charge with distributed power (August)

It can be seen that the difference is relevant. Losses in distributed power are lower and the system is more energy-efficient. Simulation has been done twice, during two different weeks corresponding to wet season. Therefore, it can be concluded that connecting the panels in a more distributed manner rather than centralized is better. In summary, the grid would consist in 12 solar panels (2 solar panels connected in parallel per house). The other dismissed option included 6 extra panels connected also in parallel but altogether in one edge of the grid.

Another interesting fact is discovered when comparing the state of charge using different converter topologies. Beforehand, it was seen that the best topology was connecting converters to both PVs and batteries. Maximum Power Point was reached while reducing losses.

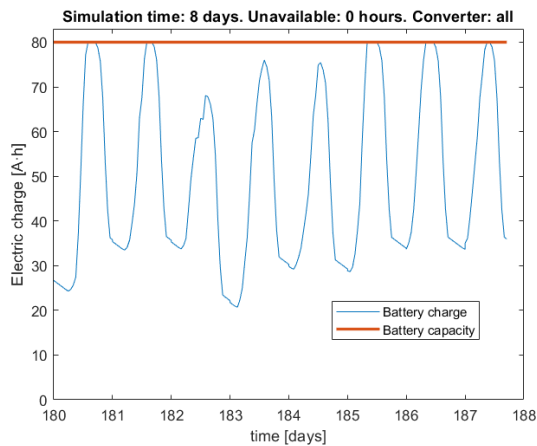


Figure 44: State of Charge during one week with PV and battery converters (June)

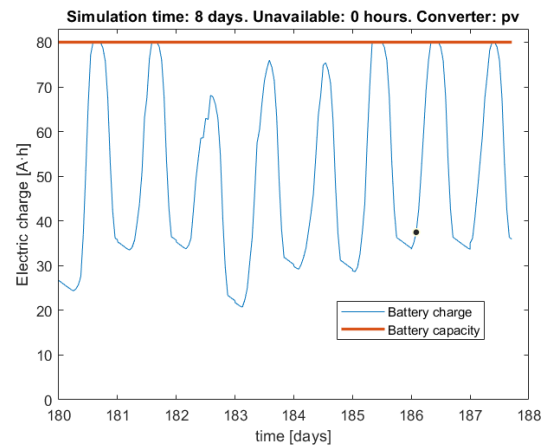


Figure 45: Same state of charge with PV converters (June)

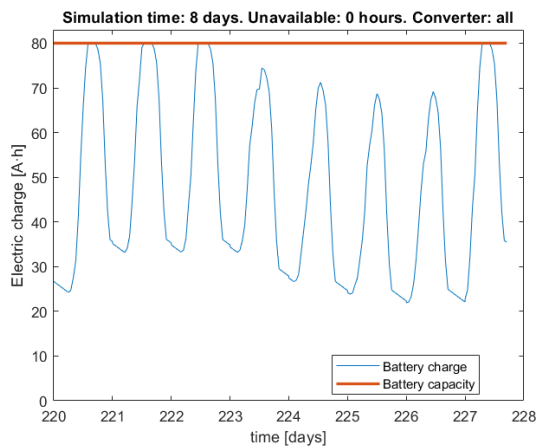


Figure 46: State of Charge during one week with PV and battery converters(August)

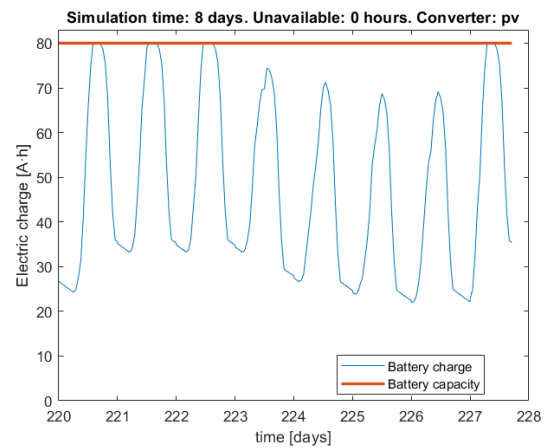


Figure 47: Same state of charge with PV converters

Although using converters everywhere might be the best option, the use of converters only in the solar panels also maximizes generation. Losses were found higher before but, as shown above, this difference is tiny. It is important to consider that as converters are expensive and they can represent a extra charge in budget. So the system can manage without converters for batteries (see Figures 46 and 47).

Finally, it's good to keep in mind that the sizing has been done for the wet season. Having a quick look at the plot during dry season (Figure 48), it's seen that a little bit of energy is lost because generation is higher than consumption and battery capacity is not higher enough. Nevertheless, this means that the user will have more energy during the day to consume. For example, using the fridge for a couple hours or more hours of TV and fan.

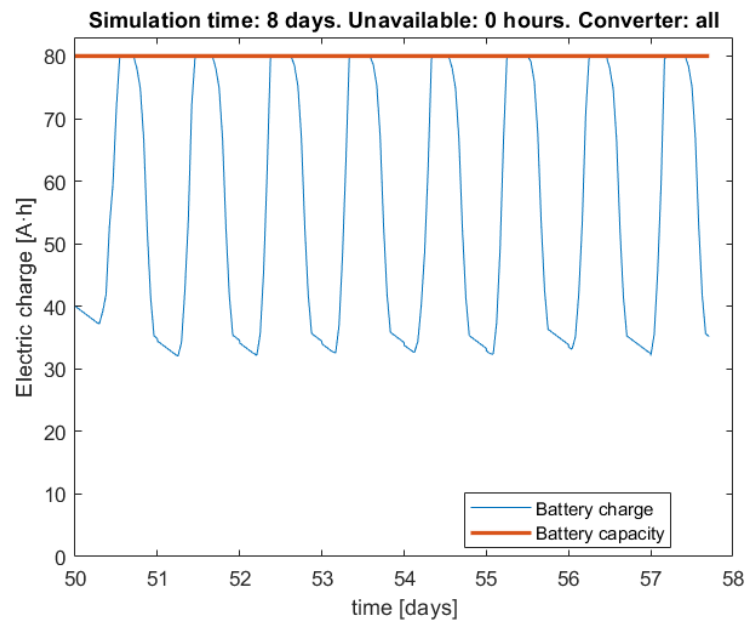


Figure 48: Continuous-time battery state of charge during dry season (8 days in February)

6 Environmental impact

6.1 Materials involved in a solar panel

Solar energy has evolved exponentially lately, giving rise to new technologies and innovative materials. Nowadays, these are the most typical solar panels in market:

- Monocrystalline Silicon
- Polycrystalline Silicon
- Amorphous Silicon
- Cadmium Tellurium
- CIS and CIGS²

Although the use of thin films is increasing (Cd-Te, CIS and CIGS), polycrystalline and monocrystalline Silicon solar panels have the biggest share of the market. This section will focus on polycrystalline panels, as these are the ones used in the study.

Materials used in a silicon photo voltaic solar panel are: silicon, glass, aluminum, Tedlar and EVA [11].

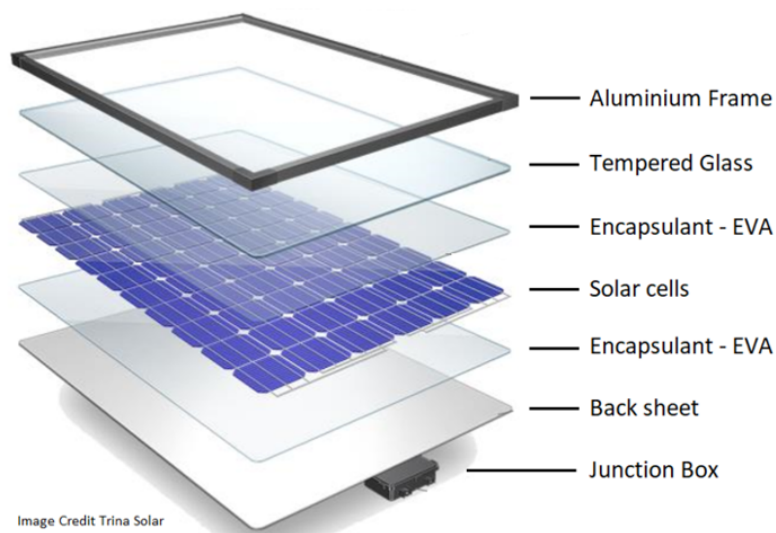


Figure 49: Materials in a Silicon Solar panel [11]

Solar PV cells are responsible for the photo-voltaic effect, converting sunlight into voltage. Each

²CIS stands for Copper Indium Selenium and CIGS for Copper Indium Gallium Selenium

solar panel possesses a great amount of solar cells electrically connected. Depending on the silicon, the performance is higher (monocrystalline ones have a better performance but they're more expensive too).

Solar cells need protection from external conditions. That's why they add a front glass to cover them. The frame protects the edges of the solar panel and gives it a solid structure. It's made of aluminum.

The encapsulate helps the solar cells to hold still and protects them from impacts or vibrations. The EVA material is the polymer used for encapsulation. Finally, the back sheet is the last layer that helps with electrical and moisture isolation and it's made of 'Tedlar'.

6.2 Manufacturing Pollution

During the manufacturing of PV solar panels, several toxic waste is produced. The most common substances emitted in the monocrystalline silicon industry are: $SiOHCl_3$, $POCl_3$ and HCl . Therefore, several preventive measures and control systems are required to manage them appropriately.

Apart from that, although solar power generates zero carbon dioxide emissions while operating, it's true that a lot of energy is used to build solar panels. This energy comes from the energy sources of the country where it's manufactured. For example, it's mostly coal in regions like China [10]. Also a lot of emissions are involved in the transportation of modules from one place to the other. In summary, the environmental footprint is not zero. That's why the EPBT³ index rate was created [8]:

$$EPBT = \text{Embodied energy}[kWh] / \text{Annual generation}[kWh/year]$$

Embodied energy represents all the energy involved in obtaining a solar panel. There is a widespread myth that this payback time exceeds solar panel lifetime. In 1970, estimated EPBT was around 20 years. Nowadays, a crystalline silicon panel will repay its embodied energy in between 4 and 1 year, depending on the manufacturing country, positioning of the PV, irradiation... Some studies show that the EPBT in Barcelona is 2.12 years if the PV is mounted on a rooftop, 1.73 years in Sevilla. This references prove that the environmental footprint is largely paid off [7].

6.3 Visual impact

Regarding the visual impact, solar panels are easily integrated in architecture. Moreover, most solar panels can be placed in rooftops regarding this project. Distributed production is different than huge solar panel facilities, where a lot of space is needed. Also in this case, they're placed in deserts and other locations that barely affect the environment.

³EPBT stands for Energy PayBack Time

6.4 PV life-cycle

Recycling is an essential developing issue in PV life-cycle. As of today, there is no legislation that dictates how to treat solar panels waste. It's true that until now few panels have arrived at the end of its life but several manufacturing companies are trying to push this sector.

Recycling a solar panel have a lot of advantages:

- Reduce the solar systems waste
- Economic and environmental benefits: as reducing the carbon footprint
- Design new solar panels that are more easily recyclable

There are several methods to recycle the materials involved in a solar panel. Just to give an insight, 'tedlar' and 'EVA' materials are removed with chemical or mechanical methods after the aluminium frame is dismantled. Later, glass and solar cells can be reused to build a new panel or also for other purposes. Structures to fix the panels to a rooftop (mostly metallic) can be easily reused [7].

7 Budget

This section tries to give an approximation of the system upgrade costs. The same solar PV have been considered. The price per Watt peak is 0.204€ [6]. Moreover, six DC converters have been considered, with Maximum Power Point control [18]. One 30 A·h battery has been taken into consideration [17].

	Units	Price/Unit(€)	Price(€)
Solar panels	6	5.10	30.60
Converters	6	48.10	288.6
Batteries	1	83.45	83.45
Total			402.6

Table 10: Budget

Conclusions

The first section of the case study includes a comparison between the old and the new adapted grid. It has been seen that losses are considerably lower in the second option, which includes one solar panel, one battery and one unit of load per household. Firstly, because now there are more than one battery and the current is distributed. Therefore, there is not only one high current that before caused more losses. Also it has been proved that the current through battery and loads are higher than the one through the solar panels. Keeping that in mind, reducing the cable length from this elements to the central node of the household will optimize the power lost due to Joule's effect.

Regarding the different converter topologies, results are similar to the previous grid model. Firstly, converter-less is the worst option as it shows higher losses and PV not generating at MPP. Secondly, converters connected to PV increase considerably the generation but losses are still high. PVs reach almost their Maximum Power Point with converters connected to each battery but the best performance arrives with converters connected to both PVs and batteries. Nevertheless, later it will be seen that the difference between the second and forth topology is negligible (as losses vary from 2.14 W to 1.28 W with full irradiation and full load and power produced is near 150 W).

During the analysis with solar panels bound to different conditions (one solar panel receives no sunlight while the others do), losses start being higher when the household battery is empty. In that situation, energy from other households needs to be transferred to the one without power source and more energy is lost due to this power exchange. If more than one panel is not active, it could be much worse but it hasn't been studied in this report.

Another important point is the work related to a more extended power supply for these rural areas in Bangladesh. One of the conclusions is that increasing the initial assumed demand (50 W per household) is essential in order to improve their quality of life. Including a fan, a TV, two LEDs, phone charger and a little fridge would lead to 170 W on peak hours. This peak hours occurs at 8 in the evening.

Consequently, a new sizing of the system was required. Considering constant demand during the year and two seasons (dry and wet), the grid needed to grow. Wet season is the less productive one in terms of generation, as rain and clouds reduce sunlight hours. Therefore, the sizing was done thinking of the conditions during wet season. Results found are the following: adding 6 solar panels (doubling the generation) and adding 30 A·h of battery capacity. With this new grid, the new computed demand in a community of 6 households is completely fulfilled. Nevertheless, (as solar energy is a discontinuous energy source) in a cloudy day no power will be produced.

Another important discovery during the sizing is the fact that adding converters to batteries might not be the best option. Power losses reduction is insignificant compared to the amount of energy produced. Therefore, using converters only for the solar panels is the most energy-efficient topology, as converters connected to batteries would be an over cost.

Finally, an environmental analysis has been done in order to understand not only the impact of this project but also the recycling possibilities. It has been realized that considering the en-

ergy involved in the manufacturing solar panels, the CO_2 footprint is not zero. Nevertheless, this energy will be paid off after between 1 and 4 years as the solar panels used are made of silicon.

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Annexes

Annex I: Nodal analysis method

In order to solve the calculations of the grid analysis, the nodal method is used. The circuit consists on PVs, batteries and loads. These elements are modelled as voltage sources with a series resistances and then are transformed to their Northon equivalent. Then, the nodal equations take place: $I = YV$. V represent the nodal voltage matrix and I represents the nodal current matrix.

Y represents the admittance matrix. This one is obtained from a matrix called 'distances' defined by the user. This 'distances' matrix (explained in detail in further annexes), computes the distance of cable in meters between all the nodes of the system. If there is no cable between nodes 1 and 6, the consequent position in the matrix will be 0.

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdot & \cdot & y_{1m} \\ y_{21} & y_{22} & & \cdot & y_{2m} \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ y_{m1} & y_{m2} & \cdot & \cdot & y_{mm} \end{bmatrix}$$

The diagonal elements y_{ii} are the sum of all the conductances connected to that node while the off-diagonal elements y_{ij} are the sum of the conductances connected between these two nodes.

The piece of code below shows the iterative method that solves all the simulations. Basically, two nominal vectors are created: I_{node} and V_{node} , corresponding to the nodal voltage and nodal current. Then, the nodal method is used (considering the admittance matrix created after the distances between elements are computed). Also the vector V_{source} is calculated in order to know the real voltage of the elements. Then, the iteration begins until the error is less than a desired value.

```

while abs(err) > 0.000001
    % Sources vector for linear Y·V=I system
    Inode = Vnode./diag(R)+Isource;
    Inode(indexBat) = Ibat; % NOTE: fake Ibat in Isource vector
    % Solve linear system
    Vnode = Y\Inode;%nodal matrix method
    % Get real source voltages
    Vsource = Vnode + Isource.*diag(R);%from Northon to Thév.
    Vsource(indexBat) = Vbat;%fix battery voltage

    % Compute error and next estimation
    err = 0;
    for j = 1:length(Isource)
        switch(type(j))
            case(1)%case solar panel or battery
                err1 = ferr(Vsource(j),Isource(j),Pmax);
                derr1 = fderr(Vsource(j),Isource(j));
            case(-1)% case load
                err1 = fLerr(Vsource(j),Isource(j),Pload);
                derr1 = fLderr(Vsource(j));
            case(2)% case solar panel not active
                err1 = fLerr(Vsource(j),Isource(j),0);
                derr1 = fLderr(Vsource(j));
        end
        if type(j) ~= 0
            err = err + abs(err1);
            Isource(j) = Isource(j) - err1/derr1;%Newton it. method
        end
    end
end

```

Figure 50: Matlab code iterative program

Annex II: Description of the grid

Matrixes used to define the grid are two: 'distances matrix' and 'type matrix'.

'Distances' compute the distance of cable between nodes (later transformed automatically with a MATLAB program to the admittance matrix).

$$dist = \begin{bmatrix} 5 & 0.01 & 0 & . & . & . & . & . & . & 0 \\ 0.01 & 1 & 0.01 & 0 & . & . & . & . & . & 0 \\ 0 & 0.01 & 1 & 10 & 0 & . & . & . & . & 0 \\ . & 0 & 10 & 5 & 0.01 & 0 & . & . & . & 0 \\ . & . & 0 & 0.01 & 1 & 0.01 & 0 & . & . & 0 \\ . & . & . & 0 & 0.01 & 1 & 10 & . & . & 0 \\ . & . & . & . & 0 & 10 & . & . & . & 0 \\ . & . & . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & . & 0.01 \\ 0 & 0 & 0 & 0 & 0 & 0 & . & . & 0.01 & 1 \end{bmatrix}$$

This is a 18x18 matrix where the numbers of the diagonal are 5, 1 and 1 periodically. It means that there are 5 meters from the PV (rooftop) to the central node of the household (or node n) and 1 meter from the battery and load to the central node. As mentioned before, This central node has been divided into three, using really low resistances (0.01 meters of cable) that represent the separation of the nodes. Then, the distance between households (for example $dist_{43}$) is assumed 10 meters.

The second matrix used in this analysis is the following:

$$type = \begin{bmatrix} 1 & -1 & 0 & . & . & . & . & 1 & -1 & 0 \end{bmatrix}$$

It is a 1x18 matrix (as there are 18 nodes: 6 households x 3 nodes/household). As commented before, 1 represents a PV, -1 a load and 0 a battery. This indexes are used by the MATLAB programs to identify which kind of current source is considered.

Annex III: Tier characteristics

			TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5	
ATTRIBUTES	1. Peak Capacity	Power capacity ratings ²⁸ (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW	
		Min 12 Wh		Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh		
		OR Services		Lighting of 1,000 lmhr/day	Electrical lighting, air circulation, television, and phone charging are possible				
	2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs	
		Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs	
	3. Reliability							Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
	4. Quality							Voltage problems do not affect the use of desired appliances	
	5. Affordability						Cost of a standard consumption package of 365 kWh/year is less than 5% of household income		
	6. Legality							Bill is paid to the utility, pre-paid card seller, or authorized representative	
	7. Health & Safety							Absence of past accidents and perception of high risk in the future	

Figure 51: Each Tier characteristics according to World Bank Group